The MODIS TEBs calibration and look-up table delivery process for Collections 6 and 6.1

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ABSTRACT

MODIS is a cross-track, whisk-broom scanning imaging radiometer with a double-sided scan mirror that collects data in 36 spectral bands. Sixteen of the 36 MODIS spectral bands are Thermal Emissive Bands (TEBs) whose spectral wavelengths range from 3.5 μm to 14.4 μm. The TEB detectors are calibrated on a scan-by-scan basis using a quadratic calibration algorithm by observing both the MODIS on-board blackbody (BB) and a background space view reference. Blackbody warm-up/cool-down (WUCD) events are performed quarterly to track on-orbit changes associated with the TEB detectors' non-linearity. Following each WUCD, the calibration coefficients in the quadratic algorithm, and their associated contributions to the total uncertainty, are updated and delivered through separate look-up tables (LUTs) when all update criteria are met. Afterwards, the LUTs are incorporated into the Level 1B (L1B) product. Since the Terra MODIS mission began, a steady increase in electronic cross-talk has been observed for TEBs 27–30. Starting from Collection 6.1, an algorithm has been applied using correction coefficients derived from regularly-scheduled lunar observations, with the correction LUT update dependent on its impact on the current L1B product. The MODIS Characterization Support Team (MCST) has established a comprehensive set of procedures to assure timely and accurate LUT updates, and maintain the quality and accuracy of the L1B and science products. This paper provides an overview of the current calibration and LUT delivery process for the MODIS TEBs in Collections 6 and 6.1.

Keywords: MODIS, thermal emissive bands, calibration, LUTs, delivery, procedure

1. INTRODUCTION

The MODerate Resolution Imaging Spectroradiometer (MODIS) is one of the key instruments onboard the National Aeronautics and Space Administration's (NASA) Terra and Aqua satellites, which have successfully completed more than 20 and 18 years of operation, respectively.[1] It was built on a strong Advanced Very High Resolution Radiometer heritage with an overall improvement in terms of its spectral range, spatial resolution, and improved coverage. MODIS is a cross-track, whisk-broom, scanning imaging radiometer that uses a double-sided scan mirror to obtain nearly-continuous Earth observations in 36 spectral bands, with wavelengths spanning from 0.4 to 14.4 μm, and produces a wide array of scientific products.[2] Among those 36 bands, bands $1 - 19$ and 26 are the reflective solar bands (RSBs) (center wavelength < 2.2 μm) covering seven visible (VIS), nine near-infrared (NIR), and four short-wave infrared (SWIR) bands, while bands $20 - 25$ and $27 - 36$ are the thermal emissive bands (TEBs) (center wavelength > 3.6 μm) constituting six mid-wave infrared (MWIR) and ten long-wave infrared (LWIR) bands. Each TEB is located on one of two temperature-controlled focal plane assemblies (FPAs) operated at a nominal temperature of 83 K. Bands $20 - 30$ consist of ten photo-voltaic (PV) detectors per band, while bands 31-36 consist of ten photo-conductive (PC) detectors per TEB.

In order to ensure sensor data quality throughout the entire mission, MODIS includes a set of on-board calibrators (OBCs): a solar diffuser (SD) with its corresponding SD stability monitor (SDSM) for RSB calibration, a blackbody (BB) target for TEB calibration, and a spectroradiometric calibration assembly (SRCA) for sensor spectral and spatial characterization.[3–7] The TEBs are calibrated on-orbit on a scan-by-scan basis by observing

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a large aperture, V-grooved BB controlled at a constant temperature of 290 K for Terra and 285 K for Aqua. A space view (SV) port provides a view of deep space each scan, which is used to determine the background signal. The BB temperature is measured by 12 evenly-spaced thermistors that were characterized pre-launch with traceability to the National Institute of Standards and Technology (NIST) temperature scale. Even though both the Terra and Aqua MODIS instruments have operated well beyond their design lifetimes of 6 years, most TEBs (except Terra MODIS TEBs $27-30$) have shown excellent stability, with long-term detector gain changes within 2% and 3% for Aqua and Terra MODIS, respectively. Since mission beginning, a steady increase in electronic cross-talk has been observed for the PV LWIR bands in Terra MODIS. A moon-based correction has been applied throughout the entire mission in the Terra Collection 6.1 (C6.1) calibration algorithm.[9]

The high-quality remote sensing data from the MODIS instruments are used to produce more than 40 science products that are helpful in studying the Earth's land, oceanic, and atmospheric systems by the global scientific community. The MODIS Characterization Support Team (MCST) is responsible for the development, maintenance, and improvement of various calibration algorithms to support continued operation and high data quality. The calibration look-up tables (LUTs) used by the operational Level 1B (L1B) data production algorithms are updated regularly by MCST. The purpose of this paper is to describe the various LUTs associated with the MODIS TEBs and discuss improvements in the calibration methodology and algorithm in C6.1 over its preceding C6.

2. TEB CALIBRATION AND COLLECTIONS HISTORY

2.1 On-orbit calibration

The MODIS TEBs calibration is based on a quadratic algorithm that converts the sensor's digital response to calibration radiance (L_{cal}).[7,8] While the dominant radiance contribution comes from the BB, there are also minor contributions from the scan mirror and instrument's cavity. The Terra and Aqua MODIS TEBs linear calibration coefficient, b_1, is derived using L_{cal} (Eqs. 1 and 2), the calibration offset (a_0) and quadratic (a_2) terms, and the BB's digital response given in digital counts (dn_{BB}). The calibration radiance can be estimated as:

$$L_{cal} = RVS_{BB}\,\mathcal{E}_{BB}\,L_{BB} + (RVS_{SV} - RVS_{BB})L_{SM} + RVS_{BB}(1-\mathcal{E}_{BB})\mathcal{E}_{cav}\,L_{cav}, \tag{1}$$

where RVS_{BB} and RVS_{SV} are the responses-versus-scan-angle (RVS) at the BB and SV angles of incidence (AOIs), respectively. $\mathcal{E}_{BB}$ and $\mathcal{E}_{cav}$ represent the BB and instrument's scan cavity (CAV) emissivities, respectively, while L_{BB}, L_{SM} and L_{cav} are the BB, scan mirror (SM), and CAV spectral radiances, correspondingly. Moreover, a quadratic function is used for the calibration of the instrument's or detector's response to the BB as:

$$L_{cal} = a_0 + b_1 dn_{BB} + a_2 dn_{BB}^2. \tag{2}$$

The offset a_0 and non-linear a_2 terms are updated (if necessary) on a quarterly basis using on-orbit BB warm-up-cooldown (WUCD) calibration activities. During each WUCD, the BB temperature changes between 270 K to 315 K, and the a_0 and a_2 calibration coefficients are computed and delivered as LUTs after a careful evaluation and following a set of internal procedures. In addition to the regular scan-by-scan monitoring of the b_1 coefficient and periodical a_0 and a_2 updates, several other LUTs are also updated on an as-needed basis. Other existing specific considerations for the MODIS TEBs include: PV LWIR electronic crosstalk correction for the Terra TEBs 27-30, an optical leak correction for the Terra PC TEBs 32-36, a fixed b_1 coefficient for band 21, and a temperature-dependent gain correction for Aqua TEBs 33, 35, and 36 - during periods when the detectors of these TEBs saturate during a WUCD.

2.2 Collections History

The MODIS L1B algorithms provide radiometric calibration and are used to convert raw instrument response to the calibrated L1B product. Over the MODIS instruments' lifetimes, the L1B LUTs and production codes have evolved to the current C6.1. The initial Collection 1 was a prototype code developed prior to the Terra launch, and was not intended for use to process on-orbit data. The first official production codes for Terra and Aqua MODIS data were Collections 2 and 3, respectively. The instrument-specific L1B codes are used to process Terra and Aqua LUTs and are individually maintained under a common configuration management system. Table 1 lists the algorithm development milestones for the different MODIS L1B versions.

Table 1: MODIS L1B algorithm development milestones.[11]

L1B milestone	Date
Start coding	1993
Version 1 delivery (C1)	March 1996
Version 2 Terra launch-ready delivery	Feb 1997
Version 2 Terra L1A and geo-location compatible delivery	Sept 1997
Terra post-launch code v2.3.2 (C2)	March 2000
Terra C3	May 2001
Aqua launch-ready C3	April 2002
Aqua C4	Oct 2002
Terra C4	Jan 2003
Terra C5	March 2005
Aqua C5	July 2005
Aqua C6	Jan 2012
Terra C6	Aug 2012
Terra C6.1	March 2017
Aqua C6.1	Aug 2017

As the instruments age, the problems identified and lessons learned by analyzing the long-term performance of each MODIS instrument led to calibration algorithm improvements with each Collection implementing improvements over the previous version. The Terra and Aqua Collections history prior to C6, and the improvements to the initial C6 algorithm have been previously presented.[10,11] The current C6.1 algorithm has been in production since March 2017 for Terra MODIS and August 2017 for Aqua MODIS with the overall performance of both MODIS instruments meeting expectations. The MCST, with inputs from members of each science discipline, performs a set of comprehensive tests to validate the proposed changes before each Collection update.

3. LUTs ASSOCIATED WITH THE TEB CALIBRATION

3.1 a_0 and a_2 LUTs

Over the 20+ years of on-orbit operation, Terra MODIS has experienced several configuration changes (electronics and formatter), therefore the a_0 and a_2 coefficients derived from prelaunch tests are replaced with those derived from on-orbit measurements. Every quarter, the MODIS instrument performs BB WUCD calibration activity which involves cooling the BB temperature from its set point temperature to the instrument ambient temperature of about 270 K. Subsequently, the BB is heated in a step-wise fashion to its maximum temperature of 315 K and is referred to as the warm-up (WU) process. After reaching its maximum temperature, the BB heater is switched off, and the BB is allowed to transition smoothly back to its ambient condition. This process is known as the cooldown(CD) cycle. The entire WUCD activity takes about 2-3 days. Figure 1 shows a typical BB WUCD profile, including telemetry data collected before and after the activity. The a_0 and a_2 calibration coefficients are derived from a quadratic fit of each detector's response to the temperature-controlled BB data obtained during this period. The L1B LUT coefficients are band-, detector-, mirror side-, and time-dependent, and are updated as needed to track the detector performance changes on-orbit.

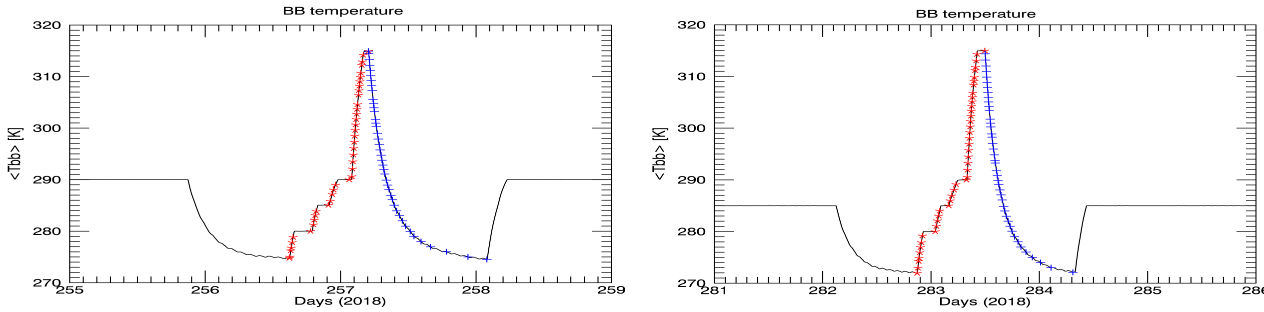

Figure 1: Example of a BB WUCD temperature profile for Terra MODIS (left) and Aqua MODIS (right). Red stars (warm-up) and blue crosses (cooldown) define the granules used to derive the offset and non-linear calibration coefficients. The black curves delineate the BB temperature.

Historically, the WU data has been used to derive a_0 and a_2, as the WU process includes stabilizing the BB at a series of plateau temperatures. However, starting from C6, only CD-derived coefficients are used due to the CD cycle being a passive process, and thus represents a more gradual rate of BB temperature change when compared to the actively-controlled process that happens during the WU cycle. The CD-derived coefficients are also closer to the pre-launch coefficient values, which were acquired over a wider BB temperature range of 170–340 K as opposed to the on-orbit range of 270–315 K.[12] In the current C6 and C6.1 algorithms, the a_0 coefficients for the PC TEBs (31–36) are set to zero. However, in the case of the Terra PV TEBs (20, 22–25, and 27–30), a small mirror side difference was observed in the L1B images. In order to remove this artifact, a_0 is set to zero for mirror-side 1, and a_0 coefficient for mirror-side 2 is derived relative to mirror-side 1.[13] The a_0, a_2 are cross-talk corrected and the correction will be discussed in later sections.

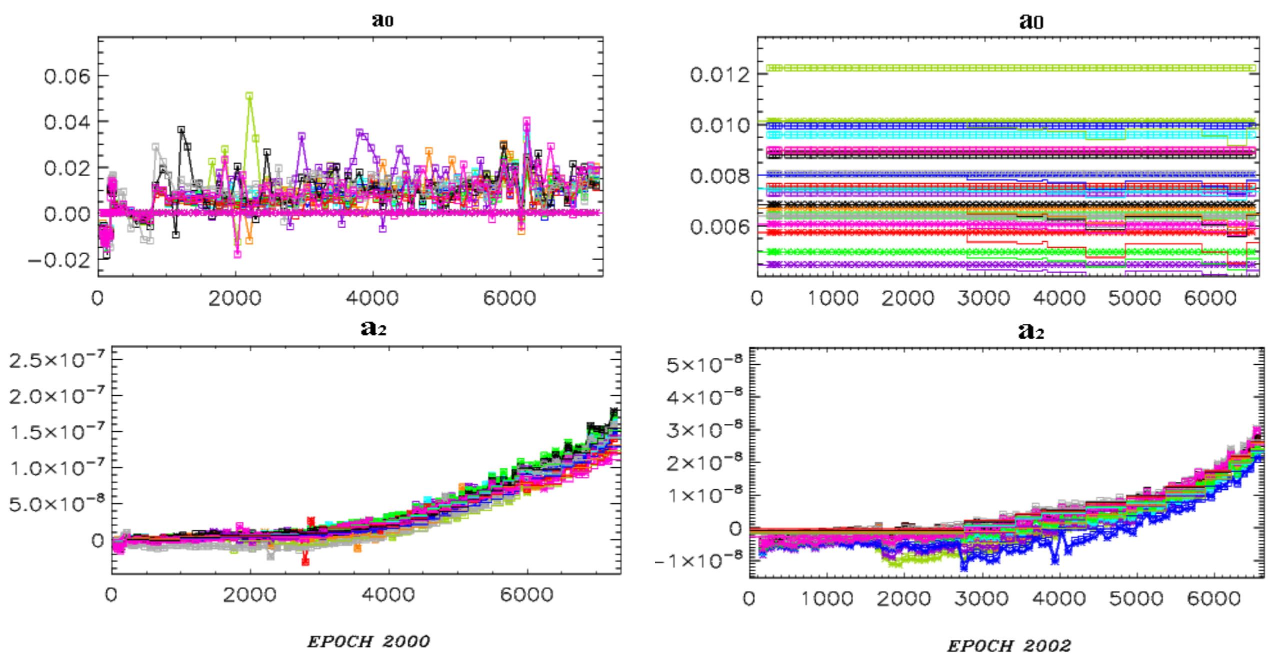

Figure 2: Band 28 a_0 (top) and a_2(bottom) trending for Terra (left) and Aqua (right) MODIS.Different color represents different detectors in the band. For Terra MODIS a_0 is set to zero for mirror-side 1

Unlike Terra, Aqua MODIS has been operating in the same configuration (i.e. B-side electronics and B-side formatter) throughout its mission. Its pre-launch coefficients were derived under the same configuration with a

much wider dynamic range are used for on-orbit calibration (except for TEBs 31 and 32). A gain change for TEBs 31 and 32 at pre-launch requires the use of on-orbit-derived coefficients. In the current algorithm, a_0 is set to 0 and a_2 is derived from the BB CD data for Aqua TEBs 31 and 32. Starting from 2008, small drifts were observed in the on-orbit-derived a_0 and a_2 calibration coefficients, which required small adjustments. A direct implementation of the on-orbit a_0 and a_2 coefficients would cause a discontinuity in the L1B data, particularly for scene temperatures beyond the BB temperature range. An iterative approach is now used to adjust the pre-launch a_2 coefficients to catch the on-orbit changes based on BB WUCD measurements.[14] The C6.1 on-orbit trends for TEB 28 a_0 and a_2 are shown in Figure 2 for both MODIS missions.

3.2 TEB 21 b_1 LUT

MODIS TEB 21 is a low-gain fire detection band with low signal levels at operational BB temperatures. Its BB digital counts are in the 20-30 range (from a full 0-4095 available range) during nominal operations, and thus the scan-by-scan b_1 values tend to have large uncertainty. Because of its low gain setting for fire detection, TEB 21 has a lower calibration accuracy requirement of 10% when compared to the other TEBs. Hence, a special consideration is given in the case of the TEB 21 calibration. In order to reduce potential scan-by-scan calibration uncertainty impacts, a fixed linear coefficient determined offline during each BB WUCD is used. In addition, the a_0 and a_2 terms in the quadratic calibration algorithm are set to zero. The strategy is currently employed in both Terra and Aqua MODIS on-orbit calibrations. The C6.1 MODIS on-orbit trends for TEB 21 b_1 are shown in Figure 3 for both Terra and Aqua. It can be seen that MODIS TEB 21 has been relatively stable over both mission lifetimes.

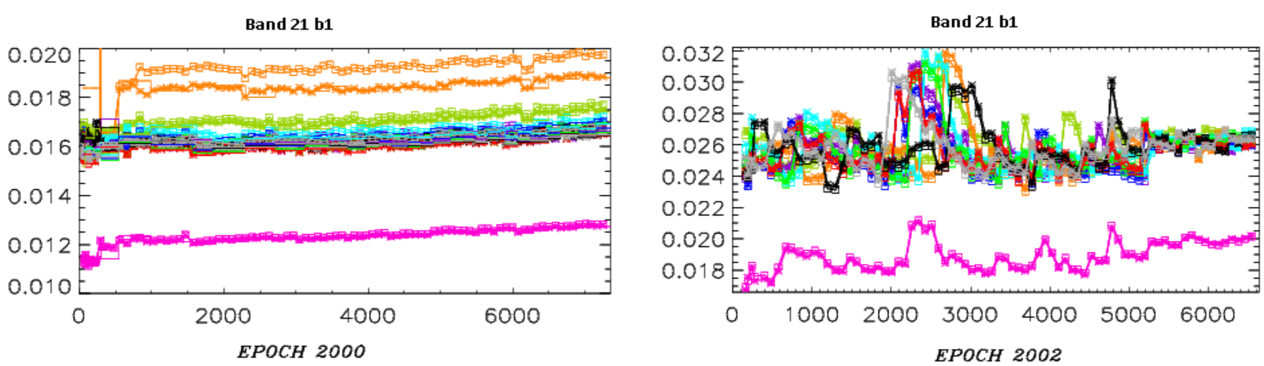

Figure 3: TEB 21 b_1 long-term trend for Terra (left) and Aqua (right) MODIS. Different color represents different detectors in the band.

3.3 PV LWIR TEBs cross-talk LUTs

Throughout the Terra MODIS mission, the PV LWIR TEBs (27–30) have shown signs of steadily-increasing electronic cross-talk in both Earth-view imagery and Moon observations, resulting in a radiometric drift and detector-to-detector differences. In February 2016, the Terra spacecraft entered safe-mode. Once the instrument returned to normal operation, the magnitude of the cross-talk contamination in TEBs 27–30 was seen to increase significantly, as evidenced in Figure 4. At this time, it became necessary to implement a correction for this electronic cross-talk contamination, resulting in a calibration algorithm change from C6 to C6.1.

The cross-talk correction for the Terra MODIS PV LWIR TEBs is derived from lunar observations, in which the source of the contaminating signal is identified based on the spatial offsets of the bands on the FPA. Using the lunar data, a set of linear correction coefficients can be derived by minimizing the contaminating signal measured outside of the main lunar image. A detailed description of the derivation and implementation of the cross-talk coefficients in Terra MODIS C6.1 can be found in Reference 9. Figure 4 illustrates an example of the detector one cross-talk correction coefficient trending from each sending band for all four Terra MODIS PV LWIR TEBs. Generally, the coefficients trends show increasingly negative values as the mission progresses. The vertical dotted line represents the Terra safe-mode.

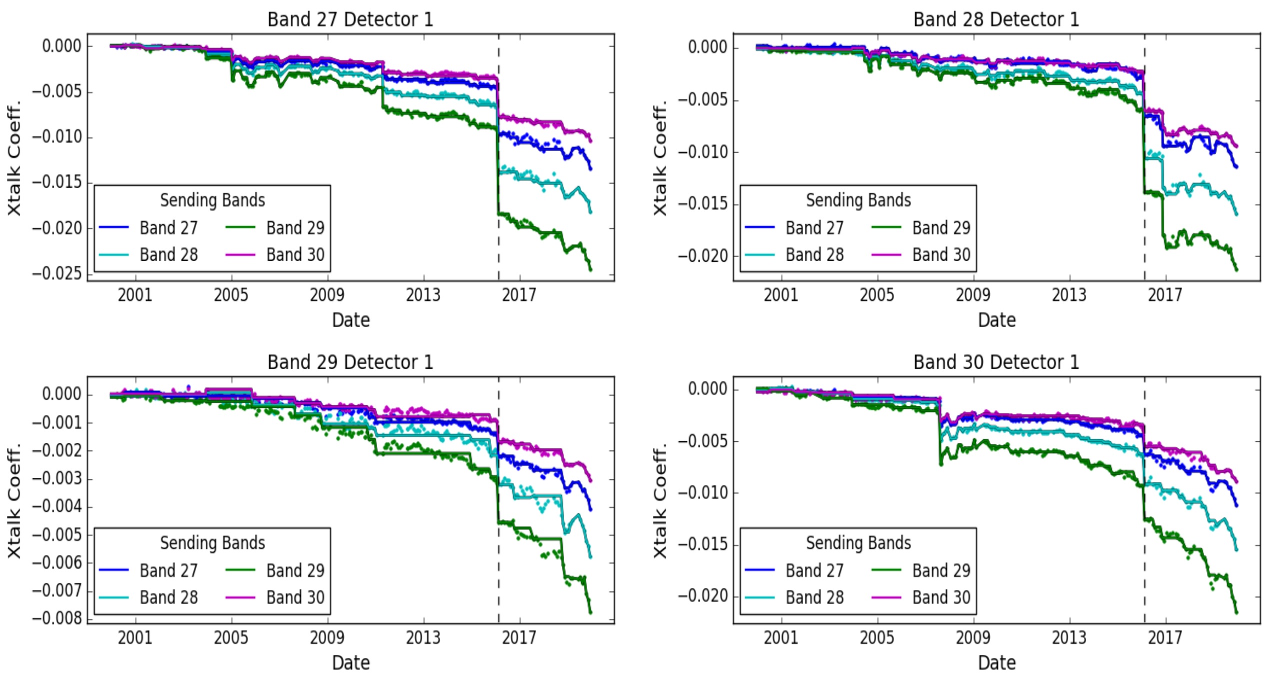

Figure 4: Example of Terra MODIS PV LWIR TEBs cross-talk correction coefficients trending for detector 1.

3.4 LWIR PC TEBs LUTs

The PC LWIR TEBs optical cross-talk for Terra MODIS was identified during pre-launch testing and occurs in bands 32 to 36. The optical leak comes from the spectral filter located near TEB 31 on the LWIR focal plane, which in turn affects TEBs 32 to 36.[15] To remove the cross-talk affect, a linear correction is applied to both the BB calibration and Earth-view radiance retrievals detector responses and is described in detail in 15. The coefficients are provided as a LUT for the optical leak correction.

3.5 Default b_1 LUTs for Aqua TEBs 33, 35, and 36 saturation issue

Aqua MODIS TEBs 33, 35, and 36 have lower saturation temperatures compared to the other TEBs, with their BB view data saturating when the BB temperature increases above a certain value (known as $T_{bb_{sat}}$).[16] Using on-orbit data, thresholds (called T_{sat}) are set at 293K, 296K, and 301K for TEBs 33, 35, and 36, respectively. These are slightly below the lowest $T_{bb_{sat}}$ over the mission.[17] Since BB data from these three bands saturates during WUCD activities, the scan-by-scan b_1 cannot be used for their on-orbit calibration during the saturation time, and thus the b_1 coefficients need to be determined alternatively (known as default b_1) for Earth-view data calibration.[17]

Since 2006, the CFPA temperature fluctuated along with the instrument environment temperature because there was a decrease in radiative cooler margin and even instances of a complete loss of the cooler margin, resulting in partial loss of temperature control for the short- and mid-wave infrared focal plane assembly.[13] Starting from the Aqua MODIS C6 a correction to account for the focal plane assembly's temperature drift and the orbital fluctuation to minimize the default b_1 error during the saturation period was implemented.

3.6 TEB uncertainty LUTs

The TEB calibration uncertainty is estimated by combining the uncertainty contributions from all of the parameters involved in the BB calibration and EV radiance calculation process. Some of these parameters and their respective uncertainties were characterized during pre-launch characterization, while others were derived and have consequently been updated using on-orbit measurements. The uncertainty associated with each parameter is considered to be independent, and the total uncertainty is estimated as the square mean summation of all

contributing factors. Because the TEB calibration algorithm is non-linear for most of the parameters used for the total uncertainty computation, their uncertainties are determined by using a perturbation approach based on Equations 1 and 2.[18]

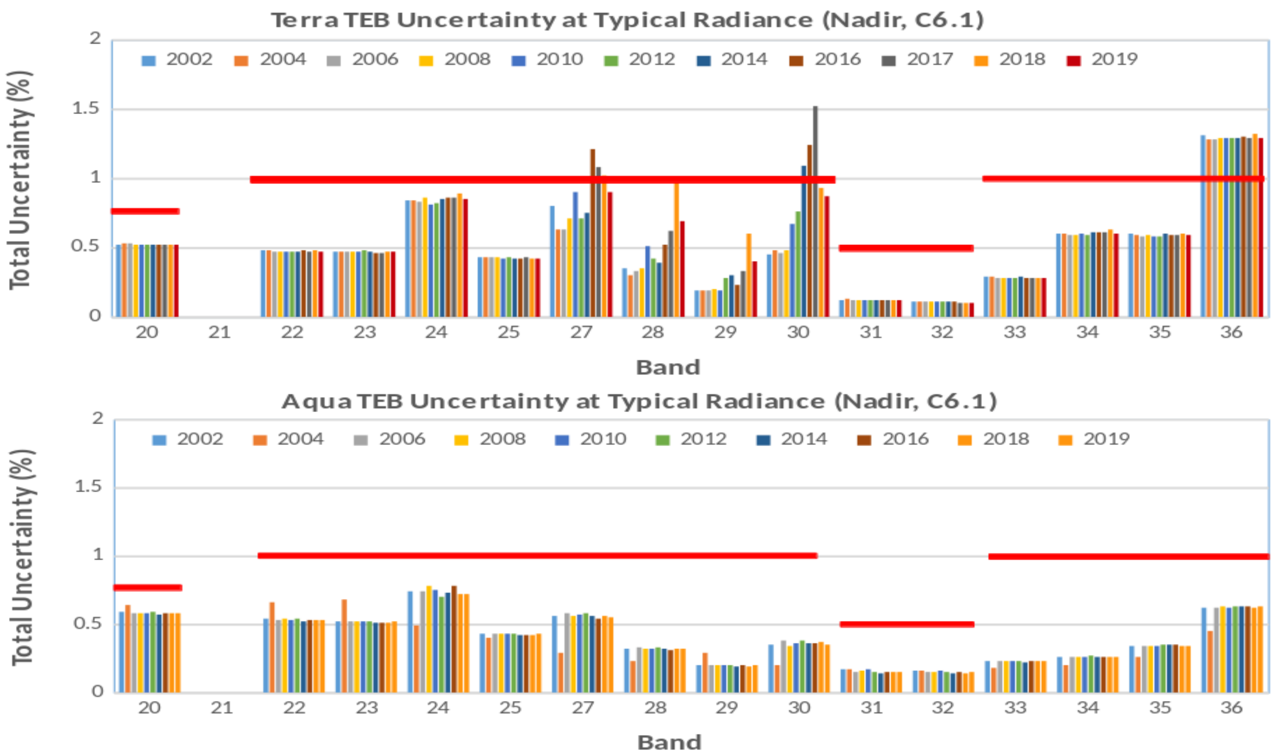

Figure 5: Terra (top) and Aqua(bottom) MODIS Collection 6.1 total uncertainties at L_{typ} for all TEBs (except TEB 21). Red horizontal lines represent uncertainty requirement.

Special considerations are given to the Terra MODIS LWIR TEBs 27-36. The optical cross-talk uncertainty in Terra TEBs 32-36 is defined as one-fourth of the optical cross-talk correction. Moreover, the Terra PV LWIR TEBs 27-30 electronic cross-talk uncertainty is estimated by applying an additional penalty at the pixel level. As a result, most detectors are generally assessed an uncertainty of 1-2%. However, some detectors in Terra TEB 27 were appraised uncertainties of 3-5% for high radiance levels late in the mission. On the other hand, the uncertainty is negligible for all detectors earlier in the Terra mission; as the detector response corrections are small.

Aside from the aforementioned and well-documented cross-talk impacts, the dominant contributors to the total uncertainty are: the detector noise and a_0 and a_2 uncertainties. Figure 5 illustrates the Terra and Aqua MODIS Collection 6.1 total uncertainties for all TEBs (except TEB 21), at typical radiance. Generally, the MODIS total uncertainties are slightly smaller for Aqua MODIS. Additional details on the MODIS TEB calibration uncertainty methodology and implementation on the L1B product can be found in Reference [18–20].

3.7 Additional LUTs

In addition to the aforementioned LUTs, another important TEB LUT is the RVS and quality assurance (QA) LUT. The QA LUts for each TEBs detector is evaluated by using noise equivalent temperature difference (NEdT) measurements at nominal BB operation values. The QA LUTs holds information about the status of the detectors using flags such as 'noisy', 'inoperable', and 'inoperable'. Characterizing the RVS was an important aspect of pre-launch testing. However, due to pre-launch measurement limitations, the Terra RVS characterization was not successful.[21] For Terra MODIS, the current TEB RVS of its scan mirror was derived using observations made

during a deep-space pitch maneuver (DSM) in early 2003.[22,23] One of the lessons learned from Terra MODIS and later applied to Aqua MODIS was to fully characterize its TEBs' RVS during pre-launch tests under many different operational configurations.[22] Another DSM calibration was performed on Terra MODIS in August 2017. Results revealed no significant change in the RVS relative to the 2003 results, with the exception of the PV LWIR bands that could not be reliably evaluated due to crosstalk impacts.[24,25]

4. LUT UPDATE PROCEDURES

4.1 a_0, a_2 and Band 21 b_1 update

The current LUT update criterion is based on a mini-L1B analysis performed on all operable detectors. The mini-L1B test, used to obtain quicker results, is a subset version of the actual L1B code. Every BB WUCD activity is evaluated to determine the need for a LUT update, with the yearly-averaged calibration coefficients (last 4 WUCD events) compared to the existing LUT values. The mini-L1B analysis uses a test granule immediately after the most recent BB CD activity, with the analysis deriving synthetic BTs over the entire temperature range and each TEB-based on the current LUT and four-point moving average based proposed LUT. A BT difference profile is calculated between the retrieved BTs from the two LUTs. Afterwards, a specification line is used to define the limit for maximum allowed temperature differences between these two LUTs. This specification line consists of two components. The first component comprises of a specification value derived from the 2*NEdT value at $L_{typical}$, while the second component is the specification derived from the 2*NEdT value at 0.3*$L_{typical}$. These specifications serve as the criteria for a LUT update. The BT differences are verified at 0.3*$L_{typical}$ and $L_{typical}$. If any detector displays BT differences outside the aforementioned specifications, a LUT update is made for all TEBs and the moving average of the a_0 and a_2 calibration coefficients over the last four BB CD events are used to replace the current LUT. Figure 6 illustrates an example of the Terra MODIS mini-L1B test mirror side one results for TEBs 29 and 30 after the BB WUCD event performed on November 2019.

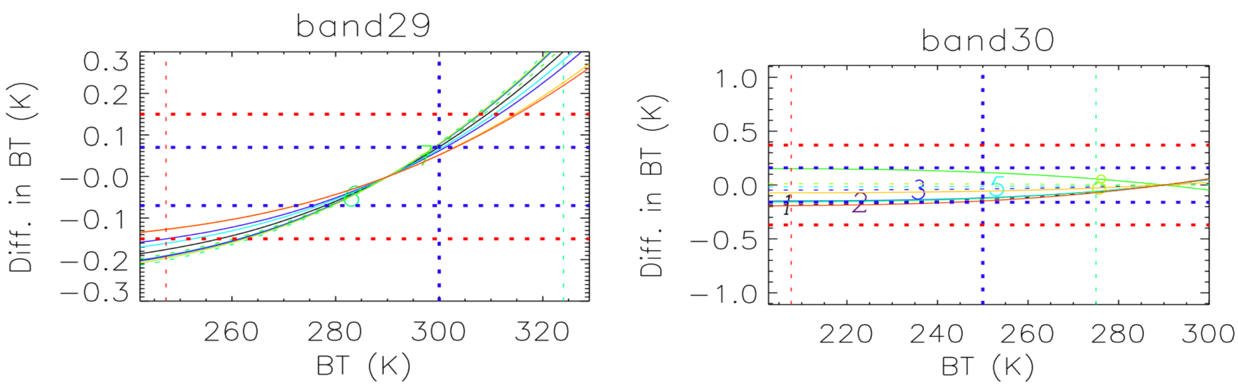

Figure 6: Mini-L1B test results for Terra MODIS TEBs 29 and 30 for mirror-side 1 after the November 2019 WUCD event. Different color represents different detectors in the band. The dashed-blue line indicates the specification at $L_{typical}$ and dashed-red line represents the specification at 0.3*$L_{typical}$.

4.2 Tera PV LWIR cross-talk update

The Terra MODIS PV LWIR TEB cross-talk coefficient LUT update criterion is also based on the mini-L1B analysis with a slight modification. From the Terra MODIS mission beginning, a slow, steady increase in electronic cross-talk has been observed for the PV LWIR TEBs, later followed by a drastic, significant rise after the Terra safe mode event on February 18th, 2016. Because signal contamination is scene-dependent and the mini-L1B analysis uses simulated digital count values, it is insufficient to accurately assess the impact of the LUT change in the case of PV LWIR bands. Hence, the impact of these LUT updates are evaluated against an orbit of actual Earth scene responses. The PV LWIR electronic cross-talk corrections are applied to the background-corrected Earth-view digital count values. The L1A granule selection process should cover a large range (variety of different scene types) of BTs. The analysis is performed using one-orbit L1A data. In order to issue a LUT

update, the same criteria described in Section 4.1 is used. The BT differences between the recently-produced PV LWIR cross-talk coefficients and current LUT are verified at $0.3{*}L_{typical}$ and $L_{typical}$. If any detector displays BT differences outside the specifications, a LUT update is made for all the PV LWIR TEBs. Figure 7 displays an example of the Terra MODIS PV LWIR TEBs 29 and 30 semi-L1B test mirror side one results after the Terra lunar roll event performed on January 2020.

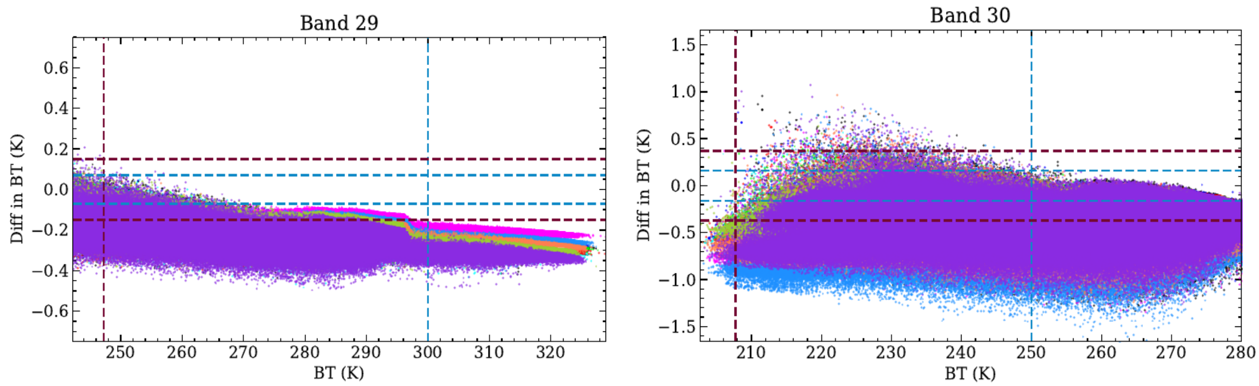

Figure 7: Semi-L1B test results for Terra MODIS TEBs 29 and 30 and mirror-side 1 after the January 2020 lunar roll. Different color represents different detectors in the band. The dashed-blue line indicates the specification at $L_{typical}$ and dashed-red line represents the specification at $0.3{*}L_{typical}$.

4.3 Delivery to L1B

Once the LUTs are generated and have been validated internally, an internal review meeting is scheduled to approve the LUT delivery. All the LUT delivery-related information - including reasons for the update and impacts on the L1B product are discussed and upon consensus the LUT is approved for delivery. Moreover, a document recording the supporting evidence, discussion, and decision reached is compiled and archived for future reference. After official approval, a message regarding the update, along with the location of the LUT and a set of test notification granules to evaluate the impact of this LUT change on the L1B product, is sent to the L1B group. The L1B group will compile the LUT and generate L1B granules - using the new LUT - for comparison. Thereafter, additional L1B comparison tests are performed to confirm the impact of the LUT update on the actual L1B product. Finally, a notification is sent to the L1B group to deliver the LUT for production.

5. SUMMARY AND FUTURE WORK

Both MODIS instruments are currently operating beyond their design lifetimes and continue to provide reliable scientific measurements. Accurate on-orbit calibration plays an important role in their success. The MCST is responsible for the development, maintenance, and improvement of the various calibration algorithms to assure continued satisfactory operation and maintain the highest possible data quality. The performance of both MODIS instruments is carefully monitored and LUTs are routinely updated. This paper is a comprehensive report of the LUTs associated with the MODIS TEBs and their respective delivery processes. Terra MODIS C6.1 includes the implementation of the PV LWIR TEBs 27-30 electronic cross-talk correction from the mission beginning through forward processing.

ACKNOWLEDGMENTS

The authors would like to thank all current and past members of the MCST in particular Amit Angal and Emily Aldoretta for their comments and review of this work.

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